C.2 New Data /TOVS

IMPROVEMENTS IN THE USAGE OF TOVS DATA

1 Introduction

Data assimilation systems (DAS) have utilized temperature and humidity information contained in the spectral radiance measurements from the TIROS Operational Vertical Sounder (TOVS) (Smith *et al.*, 1979) extensively for numerical weather prediction (NWP) and Earth Systems studies (*e.g.,* Eyre *et al.*, 1993; Derber and Wu, 1998; Andersson *et al.*, 1998; Chen *et al.*, 1999). These studies have shown that the use of passive microwave and infrared satellite observations in data assimilation systems can increase forecast skill. Considerable effort has been expended over the past two decades to achieve this result. The positive impact on forecast skill is a result of more rigorous treatment of quality control, improvements in systematic error correction schemes, and advances in data assimilation systems.

A major effort has been undertaken at the DAO to improve the assimilation of TOVS data. Over the past two years, an interactive retrieval system has been developed and implemented at the DAO. This system, known as DAOTOVS, is currently undergoing evaluation within the GEOS-DAS. DAOTOVS was designed to produce soundings over both land and ocean, and in cloudy as well as clear areas.

The initial experiments have shown positive impact in the GEOS-DAS in terms of 6 hour and 5 day forecasts. However, a full validation has not yet been completed. Here, we describe the progress to date on improvements in the usage of TOVS data. The implementation of DAOTOVS within the GEOS-DAS is expected to be operational in the GEOS-Aqua system.

2 The TOVS Instrument Package

TOVS consists of three separate sounding instruments: (1) The High-resolution Infrared Radiation Sounder 2 (HIRS2) (2) The Microwave Sounding Unit (MSU) (3) The Stratospheric Sounding Unit (SSU) (Smith *et al.*, 1979). TOVS has flown on the TIROS-N satellite and on National Oceanic and Atmospheric Administration (NOAA) operational polar-orbiting environmental satellites (POES) 6-12 and 14. NOAA 10 and 12 did not have an SSU instrument. An Advanced TOVS (ATOVS) with a HIRS instrument (HIRS3) and the Advanced Microwave Sounding Unit (AMSU) has been launched on NOAA 15.

The TOVS instruments measure the radiance from Earth passively in spectral elements or channels. The measured radiance includes thermal emission in the microwave and infrared channels and reflected solar radiation in the visible and shorter wavelength infrared channels. Radiance is commonly expressed in terms of equivalent blackbody temperature (brightness temperature), because brightness temperature is a more linear function of the atmospheric temperature and other parameters than radiance.

HIRS2 has 19 infrared channels with center frequencies ranging from approximately 670 to 2660 cm^{-1} and one visible channel. MSU has 4 channels centered near the 57 GHz oxygen cluster. SSU employs the pressure modulation technique to measure stratospheric emission in 3 channels of the 15μm CO_2 band. AMSU consists of the AMSU-A and AMSU-B instruments. AMSU-A has 15 channels including 12 in the 57 GHz band. AMSU-B has 5 channels, 3 of which are near the 183 GHz water vapor absorption line.

3 The interactive DAOTOVS 1DVAR framework

Researchers at the DAO have developed an in-house capability to use TOVS and ATOVS level 1b radiances in an interactive 1D variational system (1DVAR) called DAOTOVS (Joiner and Rokke, 2000). One of the design goals of DAOTOVS was to develop flexible modules that could be easily reused with other instruments. Some of the software was in fact used in a 1DVAR algorithm for the Global Positioning Satellite (GPS) radio-occultation data (Poli, 1999; also see section C.4 of the DAO-ATBD). In addition to the instruments described in detail here, it is hoped that this framework will be extended to other instruments such as the microwave sounders SSM/T1, SSM/T2, and SSM/IS on the Defense Meteorological Satellite Program (DMSP). These data have not yet been widely used in data assimilation systems. As the DAO moves towards a rapid update cycle (RUC) in the GEOS-DAS, the use of geostationary sounding and imager data will be explored and could also be used within this framework. Use of these new data types will depend upon available resources.

The overall processing stream for off-line and on-line DAOTOVS within the GEOS-DAS is shown in Figure 1. The main components of the diagram can be summarized as follows:

1. Stage the level 1b data.
2. Process the level 1b data (counts and calibration coefficients) to level 1c (radiances).
3. Collocate HIRS/MSU/SSU fields-of-view and average HIRS fields-of-view for cloud-clearing.
4. Collocate radiosonde data (temperature and humidity) to HIRS fields-of-view for tuning.
5. Collocate GEOS background to HIRS fields-of-view.
6. Generate tuning coefficients.
7. Process level 1c radiances into level2 temperature, humidity, and ozone retrievals at satellite footprint.
8. Create thinned or super-obbed quality-controlled Observational Data Stream (ODS) files for ingestion into the GEOS-DAS.

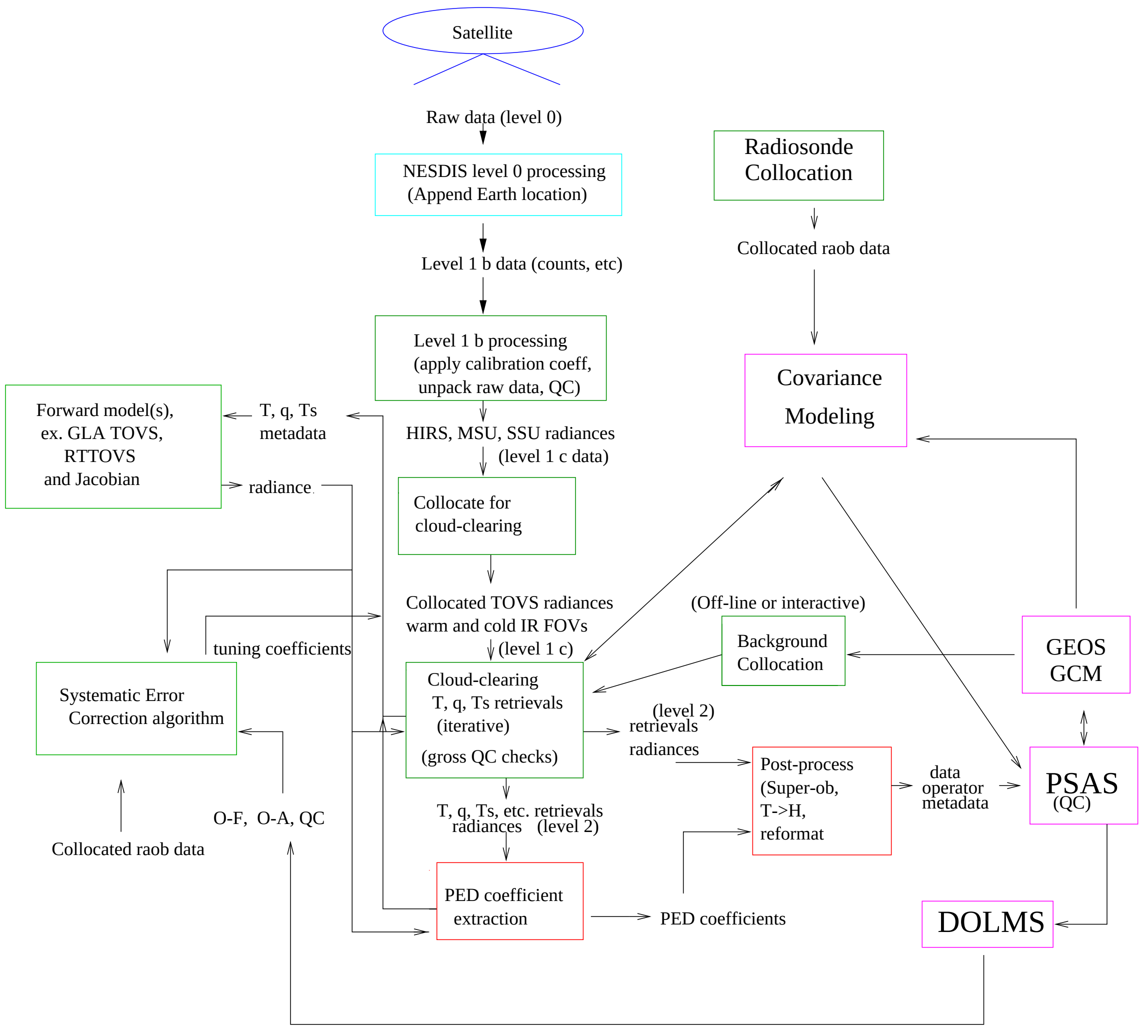

Figure 1: Flow diagram for DAOTOVS processing system

The software was designed so that it can be easily used in both off-line and on-line (interactive) modes. The off-line mode has been utilized for testing purposes. Note that the generation of partial eigen-decomposition (PED) retrievals (or compressed radiances) as per Joiner and da Silva (1998) has not been implemented at this time. This may become an option when the observation operator capability is available within the GEOS-DAS.

DAOTOVS uses a variational cloud-clearing approach. Cloud-clearing is a procedure that removes cloud radiative effects through comparison of partly cloudy adjacent pixels. The approach combines aspects of the cloud-clearing techniques pioneered by Chahine (1974, 1977), Smith (1968), McMillin and Dean (1982), and Susskind *et al.* (1984), with variational approaches used by *e.g.,* Eyre *et al.* (1993). DAOTOVS simultaneously extracts cloud-clearing parameters and information about the atmospheric and surface state from microwave and infrared observations. The variational framework ensures that the state estimate is consistent with all available measurements. The DAOTOVS cloud-clearing implementation allows for complex cloud structures including multiple cloud layers with wavelength-dependent radiative properties.

4 Preliminary results from the assimilation of TOVS 1B data using DAOTOVS

DAOTOVS retrievals have been validated using ozone data from the Total Ozone Mapping Spectrometer (TOMS), radiosondes, and the data assimilation background (Joiner and Rokke, 2000). DAOTOVS has been coupled to the GEOS-DAS forming an interactive system. This system is currently undergoing evaluation.

At the DAO, an emphasis has been placed on the middle atmosphere observations and impact studies. This has not been a focus for NWP. However, it is important for the DAO as the use of its assimilated winds, to drive stratospheric chemistry and transport models, has increased. The preliminary results shown here will focus on the stratosphere.

In the follow series of figures, comparison will be made between two assimilation experiments: (1) Control (CTRL-NES): TOVS Retrievals from the National Environmental Satellite Data and Information Service (NESDIS) are assimilated (2) Experiment (EXP-DTOV): DAOTOVS interactive retrievals are assimilated. The experimental time periods are summer 1998 and 1999. Both experiments used identical assimilation systems (GEOS 2.7.2 run at $4° \times 5°$ resolution in 1998 and $2° \times 2.5°$ resolution in 1999). The same observation and background error statistics are used in both experiments. The TOVS error statistics were optimized for the NESDIS retrievals (CTRL-NES).

A bias correction is applied to the NESDIS retrievals. No bias correction is used with DAOTOVS retrievals. The only bias correction applied in DAOTOVS is to the radiances as described in the next section.

In EXP-DTOV, SSU data were not assimilated due to an inter-instrument bias between SSU and AMSU. Therefore, prior to July 3, 1998, when the level 1b AMSU data first became available, the upper-stratospheric information came from HIRS channel 1 which has an extremely broad weighting function. NOAA-15 data (including AMSU) were not assimilated in CTRL-NES because they were not available.

A standard validation method is to generate statistics from the observed minus 6 hour forecast (O-F) fields. However, these statistics can be misleading in the case of interactive retrievals. This is because interactive retrievals contain a significant component from the model first guess. This problem particularly important in the middle and upper stratosphere where there are no other observations. For example, if the interactive retrievals did not change the first guess, the O-F statistics would have zero bias and standard deviation (indicating a perfect forecast). Instead of using interactive retrievals as the observation for verification, we can use the operational NESDIS retrievals. The NESDIS retrievals do not incorporate a model as the first guess. However, it should be noted that these data are assimilated in CTRL-NES.

Figure 2 shows the geopotential heights presented to the assimilation system at 10 hPa. Note the significant differences between the NESDIS and DAOTOVS data. Similar patterns and magnitudes of the differences between NESDIS and DAOTOVS were observed up to the topmost analysis level. The incomplete coverage in the top panel is due to an equal-area thinning algorithm that is applied to the DAOTOVS data before they are ingested.

Figures 3 and 4 show NESDIS and DAOTOVS retrieved temperatures at 2 mb, respectively. These figures show data available for a single day. The DAOTOVS temperatures were generated off-line (non-interactively). A scan angle bias and smoothing effect on the temperatures due to mapping are apparent seen in the NESDIS temperatures. These features are not present in the DAOTOVS temperatures. Finer scale thermal structures can be identified in figure 4.

Figure 5 shows that more radiosonde heights are accepted by the on-line quality control at 30 hPa in EXP-DTOV. Similar results were obtained at other pressure levels and for winds as well as geopotential height. This may be due to more consistency between DAOTOVS and radiosonde data.

Figures 6-7 show the bias and standard deviations of the 6 hour observed minus forecast (O-F) departures with respect to the NESDIS TOVS retrievals at 2 hPa. Even though the NESDIS TOVS data are assimilated in CTRL-NES, the forecasts from EXP-DTOV agree better with the NESDIS TOVS retrievals than in CTRL-NES.

Similar improvements in EXP-DTOV as compared with CTRL-NES were also seen in June 1998 before the introduction of AMSU data. This indicates that some of the improvements in EXP-DTOV are due to the interactive retrievals, and some are due to the introduction of AMSU data. However, the O-F departures for CTRL-NES were significantly smaller in June so that the degree of improvement was not as dramatic. Improvements in EXP-DTOV over CTRL-NES using this metric are seen at all altitudes down to the surface. However, the improvements diminish towards the surface.

The current statistics package does not allow for similar O-F comparisons with radiosondes. This is because a different sample of radiosonde data are accepted data in each experiment. Given that more radiosonde data were accepted in EXP-DTOV, the radiosonde statistics still showed slight improvements in EXP-DTOV over CTRL-NES.

Five day forecasts have also been generated. The anomaly correlation and RMS statistics show a positive result on average. However, the degree of improvement depends upon which analysis is used as verification. There are currently not enough forecasts

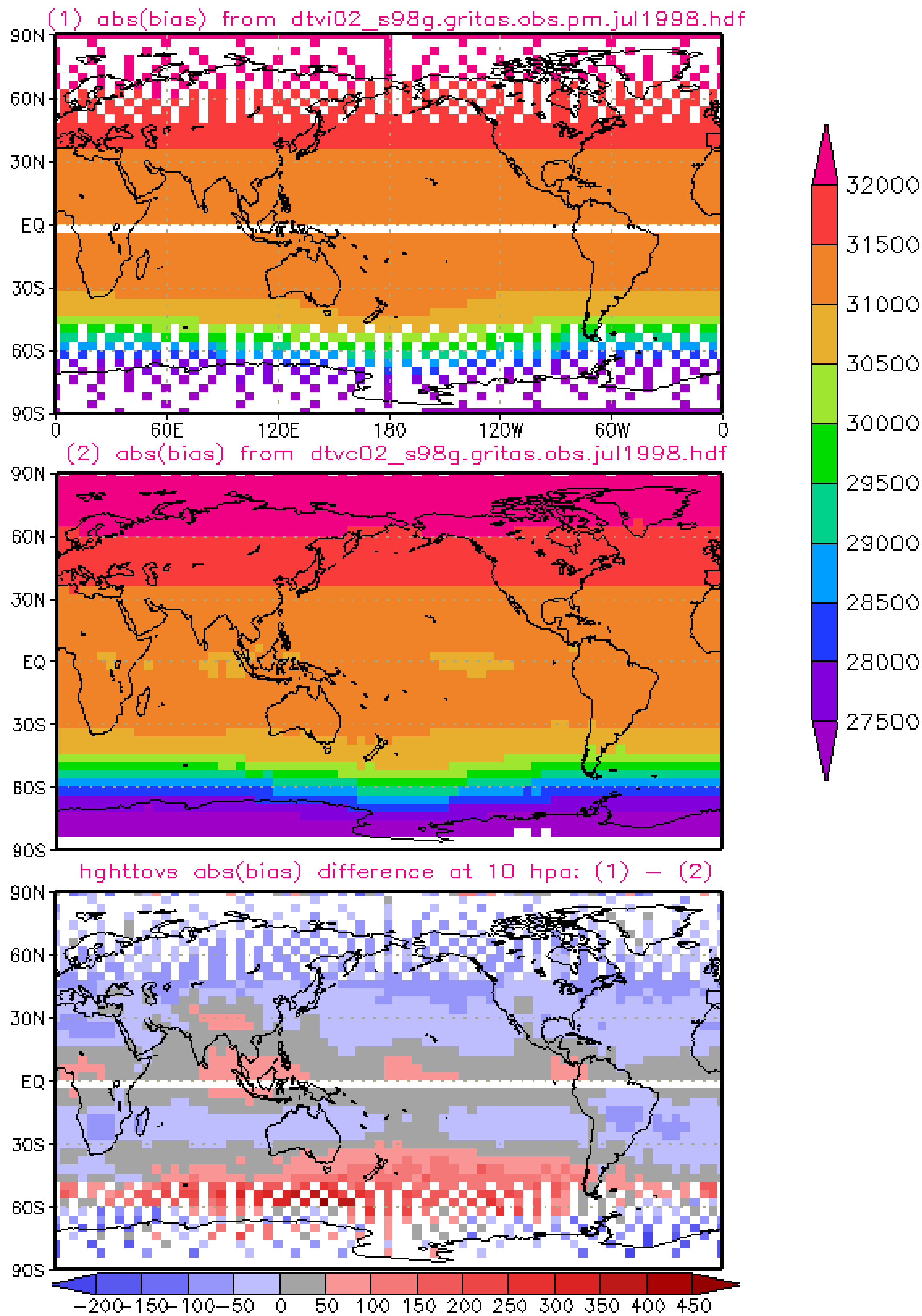

Figure 2: Top panel: DAOTOVS geopotential heights (in meters) at 10 hPa (monthly mean for July 1998); Middle panel: NESDIS TOVS geopotential heights at 10 hPa; Bottom panel: Difference between top and middle panels

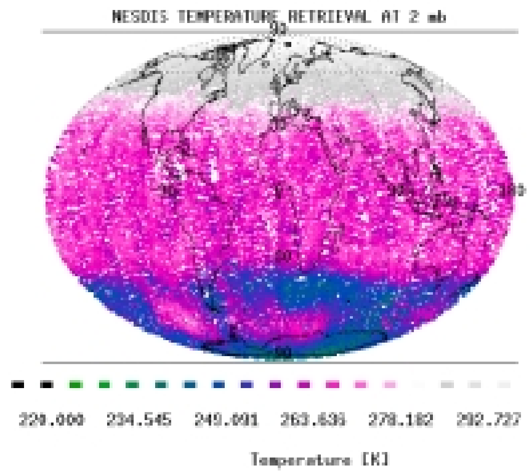

Figure 3: 2 mb temperatures on July 3, 1988 from the NESDIS TOVS retrievals

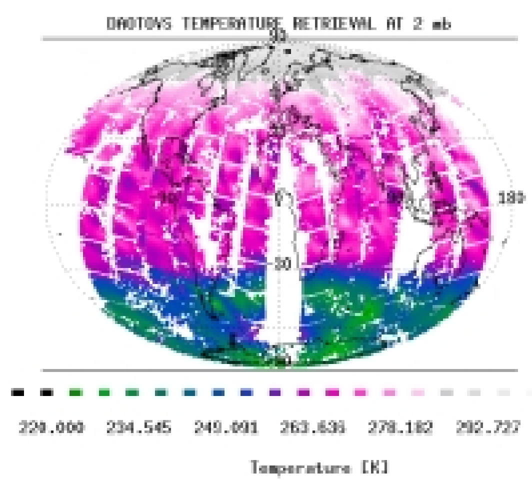

Figure 4: Similar to figure 3 but for DAOTOVS

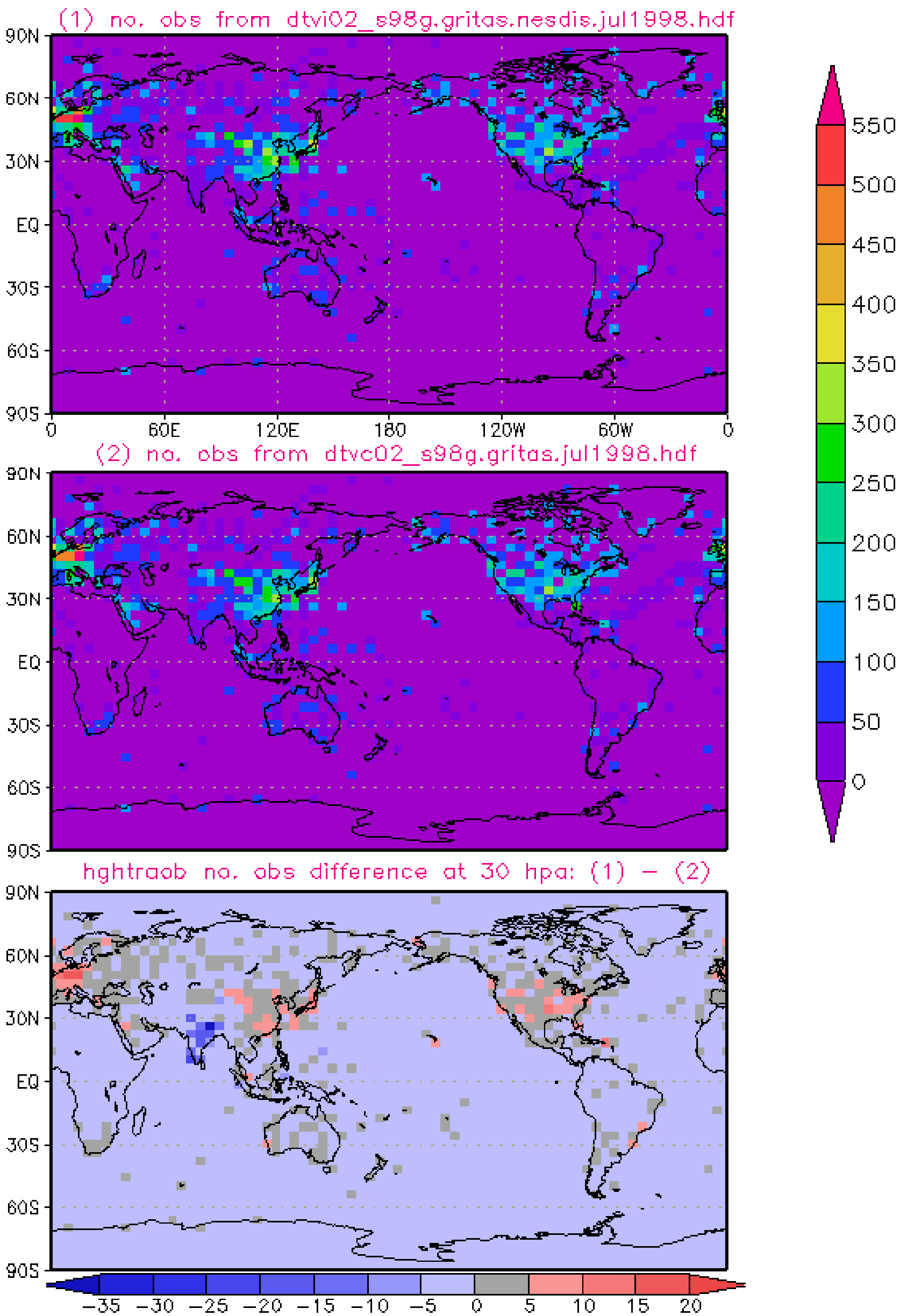

Figure 5: Similar to Figure 2 but showing the number of accepted radiosonde geopotential height observations at 30 hPa for EXP-DTOV (top) and CTRL-NES (middle).

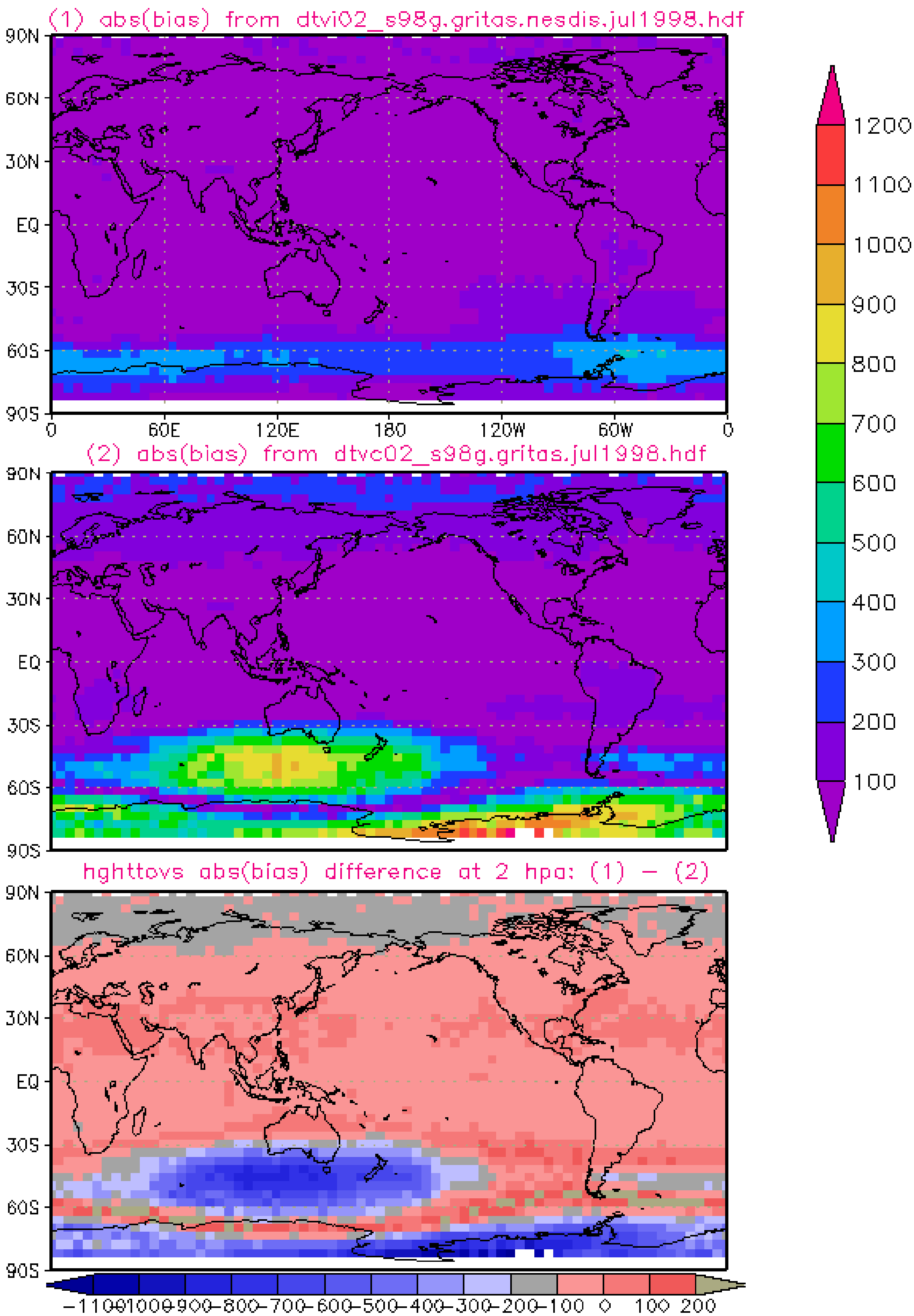

Figure 6: Similar to Figure 5 but showing the geopotential height (m) monthly mean 6 hour observed minus forecast (O-F) bias using NESDIS TOVS retrievals at 2 hPa.

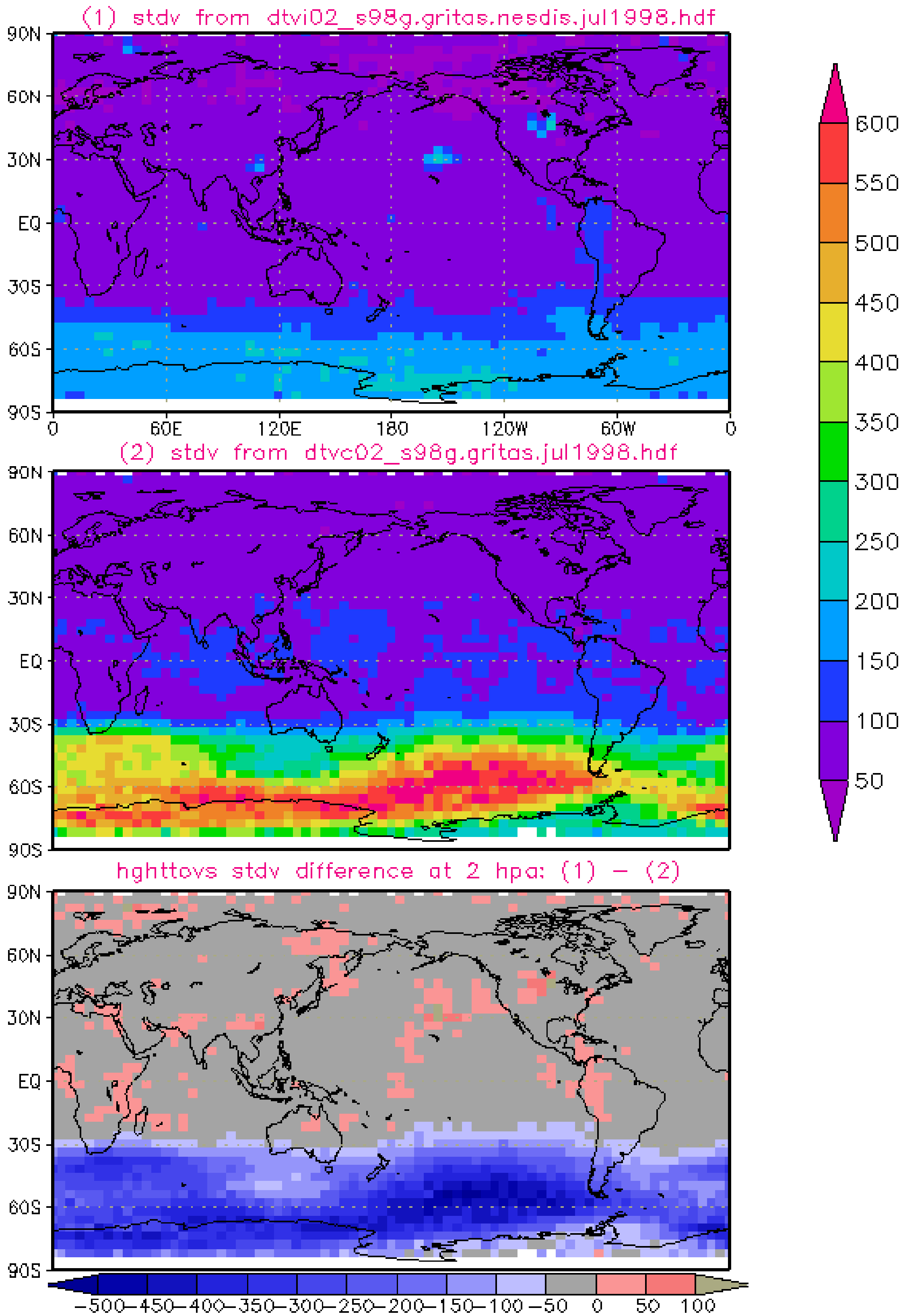

Figure 7: Similar to Figure 6 but showing the standard deviation.

available to generate reliable statistics. More forecasts are currently being run.

The two assimilations have also been compared with other climate data sets such as outgoing longwave radiation (OLR) from the Clouds and the Earth's Radiant Energy System CERES (Wielicki *et al.*, 1996). The results show no significant degradation in climate diagnostics such as clouds with EXP-DTOV even though the DAS was tuned in assimilation mode using the NESDIS retrievals.

5 Systematic error correction for radiances

There has been a focus at the DAO on systematic errors and correction methods. Treatment of systematic errors is crucial for the successful use of satellite data in a DAS, because these errors can be as large or larger than random errors. The usual assumption in data assimilation is that observational errors are unbiased. If biases are not effectively removed prior to assimilation, the impact of satellite data will be lessened and can even be detrimental. Treatment of systematic errors is important for short-term forecast skill as well as the creation of climate data sets.

A systematic error correction algorithm has been developed as part of DAOTOVS. This scheme corrects for spectroscopic errors, errors in the instrument response function, and other biases in the forward radiance calculation for TOVS. Such algorithms are often referred to as "tuning" of the radiances. This parameterization has been applied to the HIRS2 9.6μm channel (channel 9), which is affected by ozone, using collocated ozone profiles from the Solar Backscatter UltraViolet (SBUV) radiometer (Joiner *et al.*, 1997).

A comparison of DAOTOVS and several other methods used to correct systematic errors has been performed with similuated data and collocated radiosonde data (Joiner, 1997). This comparison showed that the DAOTOVS parameterization was better able to account for the complex, air-mass dependent biases that are seen in the differences between TOVS radiance observations and forward model calculations. This is because the DAOTOVS parameterization includes scaling factors for fixed gas and water vapor transmittances that are applied to the radiative transfer model. Therefore, the tuning parameters are more physically based.

Figure 8 shows brightness temperature biases (observation minus computed from radiosondes) for MSU 2 averaged over one month before and after correction. Both the scan angle and latitude dependence of the biases are much reduced with the DAOTOVS correction scheme. Figure 9 shows that the bias correction not only reduces the constant bias in the residuals, but also reduces the standard deviations. The reduction in standard deviation for some channels is quite significant.

This scheme is unique in that it uses collocated radiosondes as the unbiased state estimate rather than that of a short-term forecast from the general circulation model (GCM) used in the assimilation system. Other NWP centers have experienced difficulties using a short-term GCM forecast as the unbiased truth. This is because GCM's can also have significant biases (*e.g.,* Tony McNally, Satellite Data Assimilation Workshop, 1999).

While radiosonde data may be more unbiased than a forecast, the use of radiosondes has its own set of problems. Stringent quality control must be applied to the radiosonde data and some radiosonde types may need to be excluded as a result of significant biases.

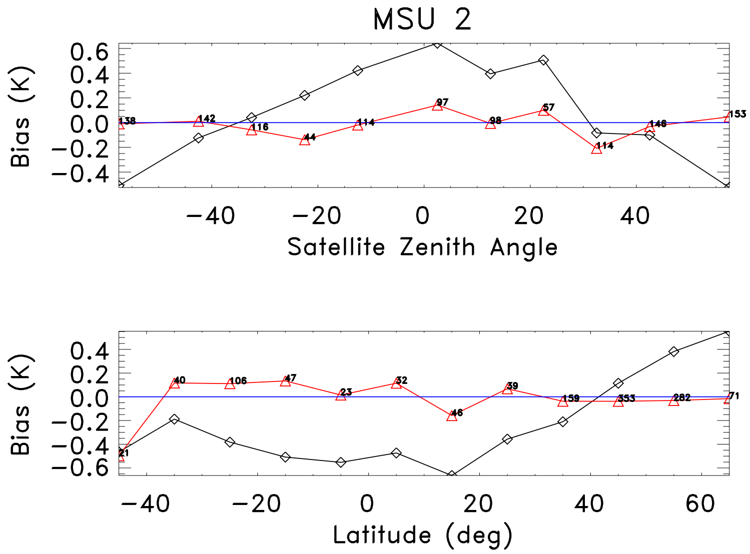

Figure 8: Radiosonde brightness temperatures bias and standard deviation for MSU channel 2. Light, triangles: after correction; dark, diamonds: before correction. The number of collocated radiosondes in each bin is indicated next to the tune values.

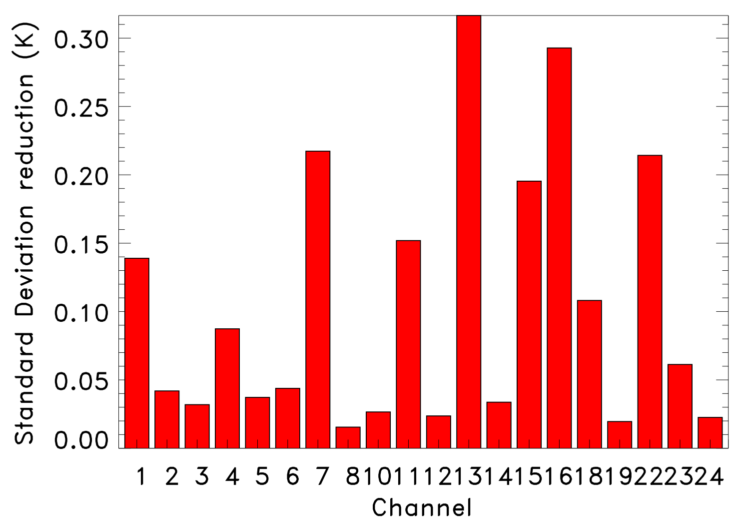

Figure 9: Observed minus computed (from radiosonde) brightness temperatures averaged over one month (January 1992). HIRS channels left, MSU channels right.

The radiosonde matchups for tuning must be done in clear conditions, and radiosondes used for tuning stratospheric channels must reach acceptable altitudes. The number of collocations matching these criteria is relatively small (less than 100 per day). In addition, the radiosondes do not measure all of the surface quantities needed for a radiance calculation (*e.g.,* surface skin temperature and emissivity).

In order to be able to use the radiosonde data for tuning, we have developed a Kalman filter to estimates a limited number of tuning coefficients for each channel as well as surface parameters. The filter uses previous estimates of the tuning parameters, as well as their errors, to update the tuning parameters daily. This leads to a smooth evolution of tuning coefficients as the instrument biases may drift slowly with time. In addition, we are investigating the usage of other data (perhaps GPS) especially in the upper-stratosphere where radiosonde data are not available.

It is important to carefully monitor the accuracy of forward models and the biases in satellite data. The DAO is currently developing a monitoring system for DAOTOVS similar to those being used at operational NWP centers. For example, we will monitor statistics of observed minus computed radiances using both the model and collocated radiosondes. This will include biases as a function of satellite zenith angle and latitude.

Figures 10-11 show the bias and standard deviations of observed radiances minus those computed using collocated radiosonde data. Note the relatively small biases (< 0.5 K) in the AMSU channels (channels 3-14 on the right side of the figures). DAOTOVS currently uses the forward model of Rosenkranz (1995) for microwave channels and Susskind *et al.* (1983) for infrared channels.

The bias in HIRS 15 is much smaller on the NOAA-K satellite than on previous satellites. Similar bias reduction has been observed at other NWP centers with different radiative transfer models. These results point to improvements in instrument calibration of the NOAA 15 instruments as compared with earlier satellites. Statistics such as these will be monitored on a both a daily basis.

6 Ongoing Development and Evaluation

Improvements have been made in cloud-detection and field-of-view determination since Joiner and Rokke (2000). These improvements are currently being examined within the GEOS-DAS. The impact of cloud- and land-affected data will be evaluated within the GEOS-DAS. If these data are not producing a significantly positive impact, they can easily be removed from the DAS.

The quality of medium-range forecasts will continue to be examined as part of the impact assessment. Other diagnostics, such as using winds to drive constituent transport models, will also be used as validation.

The current experiments have only assimilated temperature data. The next step is to assimilate both temperature and humidity data. The evaluation of these experiments will involve careful comparison with independent data sets such as CERES (Wielicki *et al.*, 1996).

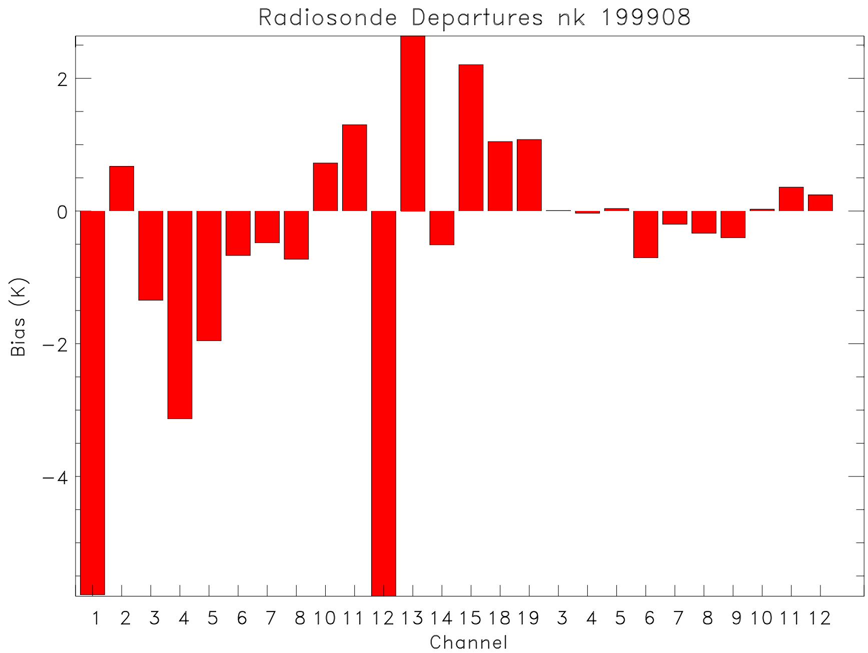

Figure 10: Bias in observed brightness temperatures minus those computed from radiosondes for NOAA 15 (nk) in August 1999. HIRS left, AMSU right.

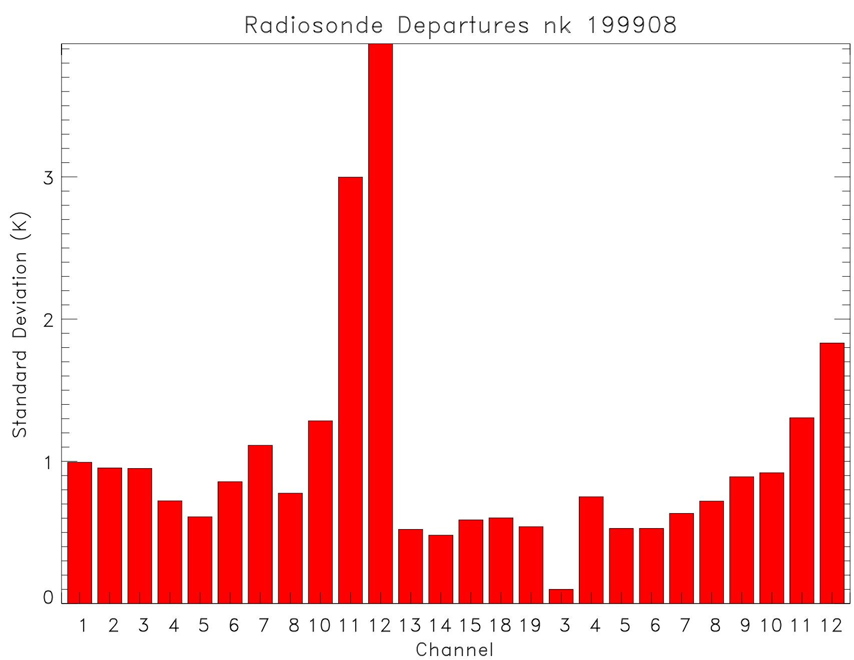

Figure 11: Similar to figure 10 but showing standard deviations.

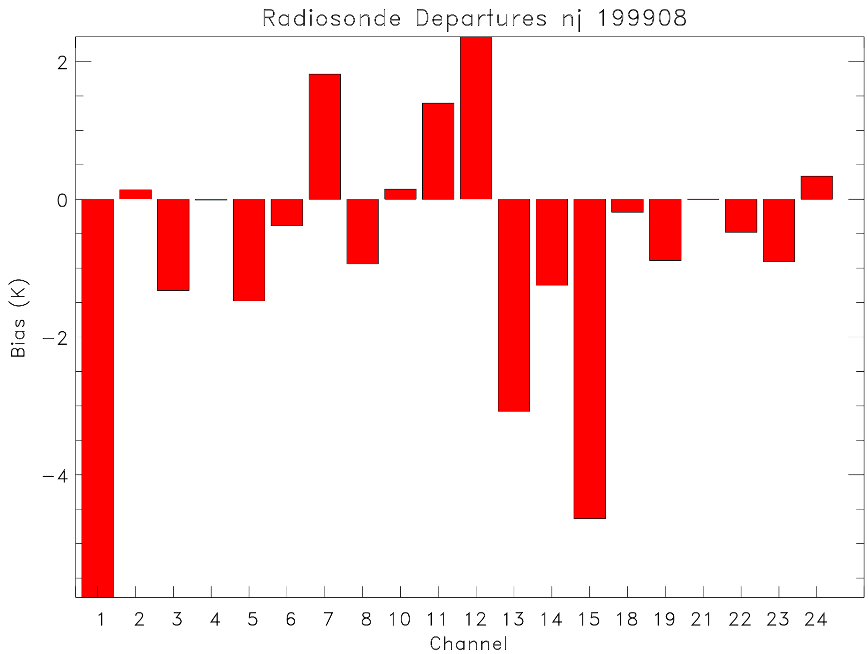

Figure 12: Similar to figure 10 but for NOAA 14.

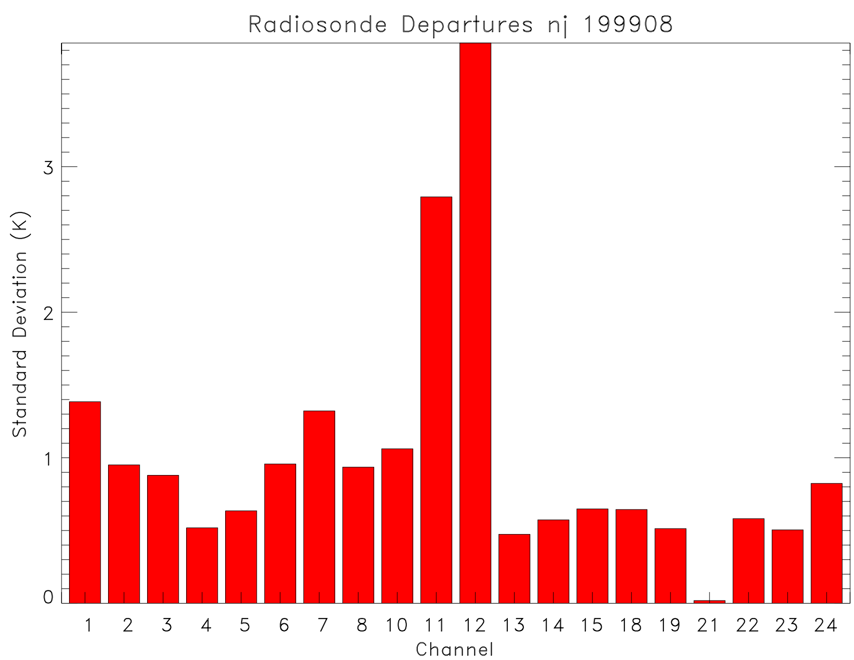

Figure 13: Similar to figure 11 but for NOAA 14.

7 References

Andersson, E., Haseler, J., Undén, P., Courtier, P., Kelly, G. A., Vasiljević, D., Branković, C., Cardinali, C., Gaffard, C., Hollingsworth, A., Jakob, C., Janssen, P., Klinker, E., Lanzinger, A., Miller, M., Rabier, F., Simmons, A., Strauss, B., Thépaut, J.-N., and Viterbo, P., 1998: The ECMWF implementation of three dimensional variational assimilation (3D-Var). Part I: Experimental results. *Q. J. R. Meteorol. Soc.*, **124**, 1783-1807.

Chahine M. T., 1974: Remote sounding cloudy atmospheres. I. The single cloud layer. *J. Atmos. Sci.*, **31**, 233-243.

Chahine M. T., 1977: Remote sounding cloudy atmospheres. II. Multiple cloud formations. *J. Atmos. Sci.,* **34**, 744-757.

Chen, M., Rood, R. B., and J. Joiner, 1999: Assimilating TOVS humidity into the GEOS-2 data assimilation system. *J. Clim.*, in press.

Derber, J., and Wu, W.-S., 1998: The use of cloud-cleared radiances in the NCEP SSI analysis system. *Mon. Wea. Rev*, **126**, 2287-2299.

Eyre, J. R., Kelly, A. P., McNally, A. P., Andersson, E., and A. Persson, 1993: Assimilation of TOVS radiance information through one-dimensional variational analysis. *Q. J. R. Meteorol. Soc.*, **119**, 1427-1463.

Joiner, J. and A. da Silva, 1998: Efficient methods to assimilate remotely-sensed data based on information content. *Quart. J. Roy. Meteor. Soc.,* **125**, 1669-1694.

Joiner, J., H. T. Lee, L. L. Strow, P. K. Bhartia, J. Miller, and L. Rokke, 1997: On the accuracy of radiative transfer in the 9.6 micron ozone band and implications for ozone remote sensing. *J. Geophys. Res.*, **103**, 19213-19229.

Joiner, J., 1997: Investigation of systematic errors and correction models. *Tech. Proc. 9th Intl. TOVS Study Conf.*, Igls, Austria, 207-216.

Joiner, J. and L. Rokke, 2000: Variational cloud clearing with TOVS data. *Quart. J. Roy. Meteor. Soc.*, **124**, 1-24.

McMillin, L. M., and Dean, C., 1982: Evaluation of a new operational technique for producing clear radiances. *J. Appl. Meteor.*, **21**, 1005-1014.

Poli, P., 1999: 1DVAR assimilation of GPS data. *Report to the Ecole Nationale de la Meteorologie, No. 664 and the NASA Goddard Data Assimilation Office*, Greenbelt, MD, USA.

Rosenkranz, P. W., 1995: A rapid atmospheric transmittance algorithm for microwave sounding channels. *IEEE Trans. Geosci. Rem. Sens.,* **33**, 1135-1140.

Smith, W. L., 1968: An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements. *Mon. Weather Rev.*, **96**, 387-396.

Smith, W. L., Woolf, H. M., Hayden, C. M., Wark, D. Q., and McMillin, L. M., 1979: The TIROS-N operational vertical sounder. *Bull. Am. Meteorol. Soc.*, **60**, 1177-1187.

Susskind, J., Rosenfield, J., and Reuter, D., 1983: An accurate radiative transfer model for use in the direct physical inversion of HIRS and MSU temperature sounding data. *J. Geophys. Res.* **88**, 8550-8568.

Susskind J., Rosenfield, J., Reuter, D., and Chahine, M. T., 1984: Remote sensing of weather and climate parameters from HIRS2/MSU on TIROS-N. *J. Geophys. Res.*, **89**, 4677-4697.

Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee, R. B., Smith, G. L., and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment, *Bull. Amer. Meteor. Soc.,* **77**, 853-868.